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CALCULATED INTERNAL RADIATION DOSE FROM INGESTION OF MEAT STERILIZED BY ELECTRON IRRADIATION

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FOREWORD

This report presents a means of estimating the magnitude of internal radiation hazard which may result from the ingestion of meat sterilized by irradiation with high energy electrons.

Beef is used as a basis for the calculations but the treatment can be employed for other foods for which radiation sterilization has been proposed.

From the results of this report, it can be stated that the amount of internal exposure is relatively small even for the highest energy considered. The calculated values represented approximately 0.1 to 2% of the average mean radiation exposure of humans, 130 mrem/year due to natural environmental radiation[12]. It points out, however, the need for further study in this area to confirm and improve the accuracy of such estimations.

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ABSTRACT

The production of radionuclides in food irradiated with high energy electrons can be predicted reasonably well with the equation presented by R. A. Meyer (1). Using this equation and others derived from the reports of the International Commission on Radiological Protection (3) it is possible to estimate the amount of radiation received by humans consuming meat irradiated by high energy electrons.

The estimated annual internal doses decrease with storage time. At the maximum energy treated the dose would decrease from a maximum of 2.36 mrem/year to a minimum of 0.113 mrem/year with a storage time of 7 days and two years, respectively. The calculated values represented approximately 0.1 to 2% of the average mean radiation exposure of humans, 130 mrem/year due to natural environmental radiation (12).

CALCULATED INTERNAL RADIATION DOSE FROM INGESTION OF MEAT STERILIZED BY ELECTRON IRRADIATION

1. Introduction

The use of electron accelerators as sources of high intensity radiation for food sterilization has shown great promise because of the relatively high dose rate obtainable as well as economic and operational efficiency.

One disadvantage of the electron accelerator is the limited penetration of the electron beam. This penetration is related to the energy of the beam electrons, i.e., in order to penetrate a thicker package it requires an increase in energy, and from this standpoint, the most efficient operation of the machine should be at the highest energy obtainable. There are costs associated with an increase of efficiency. With the accelerator, one of these costs is the production of radioactive nuclides in the irradiated sample. As the energy is increased to enable the irradiation of thicker packages the probability of inducing radioactivity is also increased.

Below some threshold energy, the reaction which causes the induced activity cannot occur. However, it appears reasonable that even above this threshold energy, there is a range which should be of little concern since the amount of induced radioactivity may not produce significant internal radiation exposure to the population eating the food.

During the years that accelerators have been considered for the sterilization of food, several reports concerning the amount of radioactivity induced in food have been published (1, 2, 5, 6, 7). Meyer [(1)] has suggested an equation for predicting concentrations of radionuclides produced in food as a function of incident electron energy and dose. This equation agrees reasonably well with available experimental data. This present report attempts to predict the internal absorbed dose to humans who eat meat sterilized by electron irradiation at several energies. Using the equation of Meyer and those of the International Commission in Radiological Protection [(3)], calculations are made for beef sterilized by electrons of energies 12, 14, 16, 18, 20, and 24 MeV and a dose of five megarads.

2. Basis of Calculations

In order to predict the dose of radiation which will be received by persons eating electron sterilized beef, it is necessary to make a series of assumptions. With each assumption made, there is further error introduced when an individual case is to be considered; however, in order to establish a

reference point from which to work, it is necessary to set conditions which may vary in their validity. At this point, the assumptions will be stated, but not defended. Under Sources of Error, the effect of the assumptions will be discussed.

In the calculations, it was assumed that:

1. Meyer's equation was valid.
2. Beef received five megarad dose at the stated energies.
3. Beef was stored for the stated times prior to ingestion.
4. 200 grams of irradiated beef were ingested per day.
5. A state of equilibrium was reached in the body with reference to the radionuclide in question, which may be expressed by equation number (2).
6. Total dose received was sum of doses from each of the radionuclides considered.
7. Radionuclides were uniformly distributed throughout the body.

3. Calculations

Meyer, after reviewing previously published information, arrives at the following equation for predicting radioactivity in food irradiated with electrons:

$$R = KAnDT^{-1} (E - E_o)^3 \qquad (1)$$

where:

R = activity in pc/gm food/D Mrads
K = 4×10^{-3}
A = atomic number of the target isotope
n = fractional abundance of the target isotope in the food

$$\frac{\text{atoms of target isotope}}{\text{atoms of target element}} \times \frac{\text{grams of element}}{\text{grams of beef}}$$

D = dose in Megarads
T = half life of product activity in years
E = initial electron energy in MeV
E_o = threshold energy for the reaction producing the product activity in MeV.

Tables I and II give the data used for the calculations in this report.

In order to establish values for an equilibrium concentration within the body of the radionuclide in question, the following form derived from the ICRP report (3) was used:

$$C = \frac{T_{eff}\, I\, f}{0.693\, m} \qquad (2)$$

where: (2a)

$$I = a \cdot R \cdot e^{-\frac{0.693 \cdot t}{T}}$$

C = the equilibrium concentration of the element in the body of radionuclide pCi/g of body

Teff = the effective half period for the radionuclide in the body in days

I = rate of ingestion of the element (radionuclide) pCi/day

f = the fraction of the ingested material remaining in the body

m = the mass of the body (taken as 70 Kg for the "standard man")

a = 200 grams of beef (see assumption 4)

t = time between radiation and ingestion

The absorbed dose in rem/year is then calculated from:

$$(AD) = \frac{C\ f_i\ \epsilon}{53.6} \qquad (3)$$

where:

(AD) = absorbed dose received by the body in rem/year

C = concentration in pCi/g of body

f_i = fraction reaching critical organ (taken as 1 for total body)

ϵ = energy absorbed by tissue in MeV/disintegration

53.6 = constant value such that units are properly converted i.e.

$$53.6 = \frac{\left(100\ \frac{\text{ergs}}{\text{g rads}}\right)\left(10^6\ \text{pCi/uCi}\right)}{\left(3.7 \times 10^4\ \frac{\text{dps}}{\text{uCi}}\right)\left(1.6 \times 10^6\ \frac{\text{ergs}}{\text{MeV}}\right)\left(3.15 \times 10^7\ \frac{\text{sec}}{\text{year}}\right)}$$

Two sample calculations are shown in order to show the general form used in the calculation. For Na^{22}, the 2.6 year half-lived isotope of sodium which is produced by a (γ,n) reaction, the following example is presented: (20 MeV electrons: 1 year storage)

$$R = KAnDT^{-1}\ (E - E_o)^3$$

$$R = \frac{(4 \times 10^{-3})\ (23)\ (5 \times 10^{-4})\ (5)}{2.6}\ (20 - 12.4)^3$$

$$R = 3.88 \times 10^{-2}\ \text{pCi/g of beef}$$

$$C = \frac{(Teff)\ (I)\ (f)}{0.693\ m}$$

$$C = \frac{(11)\ (5.92)\ (1)}{(0.693)\ (7 \times 10^4)}$$

$$C = 1.34 \times 10^{-3}\ \text{pCi/g of tissue}$$

$$AD = \frac{C\ f_i\ \epsilon}{53.6}$$

$$AD = \frac{(1.34 \times 10^{-3})\ (1)\ (1.6)}{53.6}$$

$$AD = 4.00 \times 10^{-5}\ \text{rem/year}$$

$$I = 200 \cdot R \cdot e^{-\frac{0.693 \cdot 365}{T}}$$

$$I = (2 \times 10^2)\ (3.88 \times 10^{-2})e^{-\frac{253}{949}}$$

$$I = 7.76e^{-0.266}$$

$$I = 5.92\ \text{pCi/day}$$

For P^{32} the day isotope of phosphorus which is produced by a (γ, pn) reaction with S^{34}, the following example is presented: (20 MeV, 1 month storage)

$$R = KAnDT^{-1} \quad (E - E^{\circ})^3$$
$$R = \frac{(4 \times 10^{-3})(34)\ (0.92 \times 10^{-4})(5)}{3.9 \times 10^{-2}} (20 - 10.9)^3$$
$$R = 1.21 \text{ pCi/g of beef}$$

$$I' = I\,R$$
$$I' = (2 \times 10^2)\ (1.21)(e^{-\frac{(.693)(30)}{14.2}})$$
$$I' = (2.42 \times 10^2)(e^{-1.46})$$
$$I = 5.62 \times 10 \text{ pCi/day}$$

$$C = \frac{(T_{eff})(I')(f)}{0.693\ m}$$
$$C = \frac{(13.5)(56.2)(0.75)}{(0.693)(7 \times 10^4)}$$
$$C = 1.17 \times 10^{-2} \text{ pCi/g of tissue}$$
$$AD = \frac{C\ f'\ \epsilon}{53.6}$$
$$AD = \frac{(1.17 \times 10^{-2})(1)(0.69)}{53.6}$$
$$AD = 1.51 \times 10^{-4} \text{ rem/year}$$

4. Sources of Error

The assumptions made in paragraph 2 are considered in some detail in the order in which they were listed.

1. Validity of Meyer's Equation

Meyer's equation can only be expected to predict the activity produced to within approximately a factor of 2, since the fractional abundance of the parent isotope in a given food often varies. Further, the equation is based on a simple approximation of both the photonuclear cross section and the bremsstrahlung spectra. Meyer and Burkhardt (7) have shown, however, that this equation and a graphical integration are in reasonable agreement with each other and available experimental data.

2. Beef received five Megarad dose at the stated energies

Dose to beef may vary throughout the product up to 25% under present irradiation requirements. The energy of the electrons is not monochromatic, therefore, electrons up to the maximum energy will be present in the beam. This condition will tend to lower actual production of radionuclides as compared to the theoretical production.

3. Beef was stored for the stated times prior to ingestion

No problem arises from this assumption.

4. 200 grams of irradiated beef are ingested per day

This is a relatively conservative consumption since it assumes all of the beef eaten is irradiated and that beef is eaten every day. Beef was chosen, however, since it is the most likely candidate for such an assumption.

5. A state of equilibrium is reached in the body with reference to the radionuclides in question, which may be expressed by equation (2).

This assumption is one that has been made by the ICRP in their calculations of maximum permissible concentrations of radionuclides in the human body, water, and air.

6. Total dose received is the sum of doses from each of the radionuclides considered.

There are other possible sources of induced radioactivity. One of the most significant reactions is that which produces isometic radioculides. However, according to Meyer [5] no isomeric activation has been found in foods. Another source of error might be the gamma-triton reaction which produces tritium. Meyer states that tritium has not been found experimentally above background levels in food.

Other elements than those considered in Table I and which might be present in foods could also produce radioactivity via the reactions considered. However, these elements are generally in very small concentrations and would produce negligible amounts of the radioactive products.

7. Whole body dose assumes uniform distribution of each of the radionuclides in the body

This assumption is one which leaves much to discuss. Actually, no element is truly uniformly distributed throughout the entire body. When one considers the localization of a particular radionuclide in a specific organ, then the dose to that organ will be significantly higher than the dose to the whole body. The two most significant radionuclides Na^{22} and P^{32} are relatively uniform in distribution, therefore, the dose calculations are acceptable.

For the short storage time, I^{126} represents a relatively low total body exposure 8.02×10^{-5} mrem/year, however, iodine is selectively absorbed by the thyroid gland. If the thyroid gland is considered alone, the dose would be about 5.63×10^{-2} mrem/year or nearly 1,000 times the dose to the whole body contributed by Iodine-126.

The major contributor to the internal dose to the body during short storage times, 7 days and 30 days, is phosphorus-32; after longer storage times Sodium-22 becomes the major contributor.

5. Discussion

Table I indicates the data used in solution of Meyer's equation for each of the nuclides listed.

Table II indicates the data used in the internal dose equations. Appendix I shows calculations of the effective energy per disintegration for these radionuclides for which data are not available in the ICRP report.

Table III indicates the total annual internal absorbed dose in mrem for various energies and storage times. Figure 1 shows graphically the same

information allowing for some interpolation of energies and storage times.

It is the intention of this report to present an estimate of internal dose received by persons eating electron sterilized meat and thereby demonstrating that this dose is relatively low. It is not intended to minimize the need for further experimental studies to confirm these data.

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TABLE I

Data Used in Calculation of
Radionuclide Production

Nuclide	Parent/reaction		Fraction of parent nuclide in beef	Half life of product Nuclide (years)	Threshold energy for reaction (MeV)
Na^{22}	Na^{23}	(γ-n)	5×10^{-4}	2.6	12.4
Na^{24}	Mg^{24}	(γ-p)	3.1×10^{-5}	1.71×10^{-3}	12.1
P^{32}	S^{34}	(γ-pn)	0.92×10^{-4}	3.9×10^{-2}	10.9
P^{33}	S^{34}	(γ-p)	0.92×10^{-4}	6.6×10^{-2}	18.8
S^{35}	Cl^{37}	(γ-pn)	1.47×10^{-4}	0.24	16.1
Ca^{45}	Ca^{46}	(γ-n)	3.3×10^{-9}	0.45	10.4
Cr^{51}	Cr^{52}	(γ-n)	2.5×10^{-9}	7.4×10^{-2}	12.0
Mn^{54}	Mn^{55}	(γ-n)	2.0×10^{-7}	0.822	10.2
Fe^{55}	Fe^{56}	(γ-n)	3.8×10^{-5}	2.6	11.2
Zn^{65}	Zn^{66}	(γ-n)	4.17×10^{-6}	0.671	11.0
Rb^{84}	Rb^{85}	(γ-n)	0.94×10^{-6}	9.0×10^{-2}	10.5
I^{126}	I^{127}	(γ-n)	3.5×10^{-8}	3.6×10^{-2}	9.2
Cs^{132}	Cs^{133}	(γ-n)	9.2×10^{-9}	1.7×10^{-2}	9.0

TABLE II

Data for the Dose Calculations

Nuclide	Effective Half Life (days)	Fraction of Ingested Nuclide Remaining in Body	Effective Energy Absorbed per Disintegration + (MeV/dis.)
Na^{22}	11	1.0	1.6
Na^{24}	0.6	1.0	3.6
P^{32}	13.5	0.75	0.69
P^{33}	22.8	0.75	0.086
S^{35}	76.4	1.0	0.056
Ca^{45}	162	1.0	0.43
Cr^{51}	26.6	5×10^{-3}	0.025
Mn^{54}	5.6	0.1	0.23
Fe^{55}	388	0.1	6.5×10^{-3}
Zn^{65}	194	0.1	0.32
Rb^{84}	0.047	1.0	1.63
I^{126}	12.1	1.0	0.16
Cs^{132}	0.168	1.0	0.47

+ See Appendix I for calculations of ϵ not given in reference (3).

TABLE III

Annual Dose (mrem) Calculated for Several Energies

Electron Energy	Storage Time (days)				
	7	30	180	365	720
12	8.11 (-4)	2.64 (-4)	-	-	-
14	1.92 (-2)	6.44 (-3)	4.43 (-4)	3.83 (-4)	2.94 (-4)
16	9.02 (-2)	3.18 (-2)	4.97 (-3)	4.32 (-3)	3.31 (-3)
18	2.53 (-1)	9.26 (-2)	1.87 (-2)	1.61 (-2)	1.24 (-3)
20	5.54 (-1)	2.13 (-1)	4.86 (-2)	4.11 (-2)	3.14 (-2)
22	1.29	6.18 (-1)	1.67 (-1)	9.85 (-2)	6.41 (-2)
24	2.36	1.21	3.40 (-1)	1.84 (-1)	1.13 (-1)

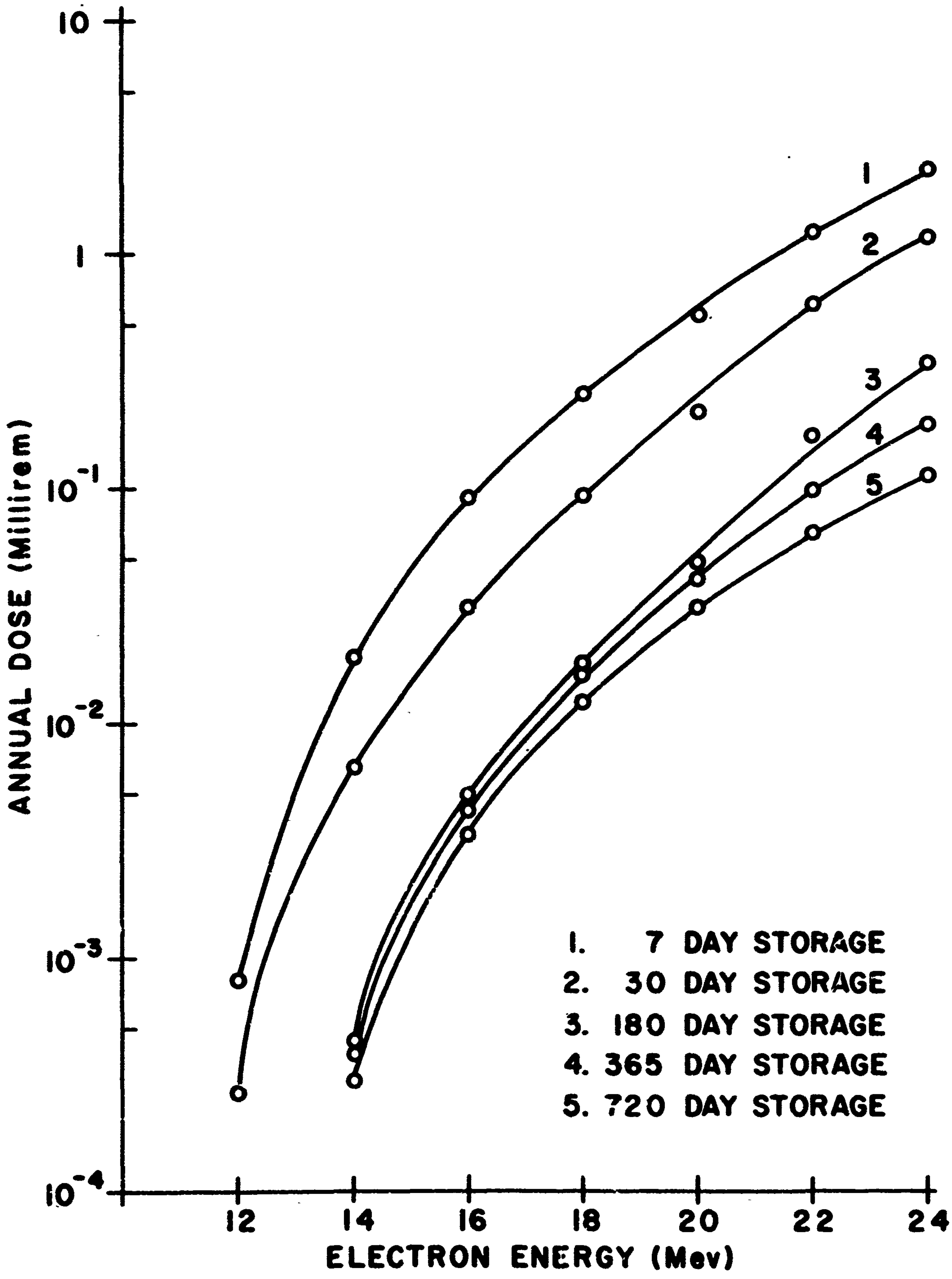

FIG I, ANNUAL DOSE (mrem) vs ELECTRON ENERGY (Mev)

APPENDIX I

Calculations of effective energy per disintegration based on the techniques described in the report of the International Commission on Radiological Protection (1959) are made for the following radionuclides:

$\underline{\underline{Na^{24}}}$ RBE = 1 (More recent terminology in personnel dosimetry uses QF (quality factor) to effectively describe the relative effectiveness of various types and energies of radiation)

n = 1
F = 1

$$E_{\beta} = 0.33\ E_m f(1 - \frac{Z^{\frac{1}{2}}}{50})(1 - \frac{E_m^{\frac{1}{2}}}{4})$$

$$E_{\beta} = (0.33)(1.40)(1)(1 - \frac{(11)^{\frac{1}{2}}}{50})(1 + \frac{(1.40)^{\frac{1}{2}}}{4})$$

$$E_{\beta} = 0.559$$

$$E_{\gamma_1} = E_m(1 - e^{-\sigma x})$$

$$E_{\gamma_1} = (1.37)(1)(1 - e^{-(0.060)(30)})$$

$$E_{\gamma_1} = 1.14$$

$$E_{\gamma_2} = (2.75)(1)(1 - e^{-(0.040)(30)})$$

$$E_{\gamma_2} = 1.93$$

$$\epsilon = E\ F(RBE) = 0.569 + 1.14 + 1.93$$

$$\epsilon_{Na^{24}} = 3.6$$

$\underline{\underline{Rb^{84}}}$ RBE = 1
n = 1
F = 1

$$E_{\beta} = (0.33)(0.91)(0.025)(1 - \frac{6.08}{50})(1 - \frac{.954}{4})$$

$$E_{\beta} = 5.02 \times 10^{-3}$$

$$E_{\beta^+} = 0.33 E_m f(1 - \frac{E_m^{\frac{1}{2}}}{4}) + 2f(0.51)(1 - e^{-\sigma x})$$

$$E_{\beta} = (0.33)(1.64)(0.56)(1 - \frac{1.28}{4}) + (2)\ (0.51)(0.56)(1 - e^{-(0.04)(30)})$$

$$E = 0.604$$

$$E_{\beta_1^+} = (0.33)(0.79)(0.44)(1 - \frac{0.89}{4}) + (2)(0.51)(0.44)(1 - e^{-(0.04)(30)})$$

$$E_{\beta_1^+} = 0.404$$

$$E_{\beta_2^+} = (0.88)(1)(1 - e^{-(0.04)(30)})$$

$$E_{\beta_2^+} = 0.615$$

$$\epsilon_{Rb^{84}} = 1.63$$

$\underline{\underline{Cs^{132}}}$

$$E = (0.67)(1)(1 - e^{-(0.04)(30)})$$

$$E = 0.468$$

$$\epsilon = 0.468$$

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13. ABSTRACT

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The estimated annual internal doses decrease with storage time. At the maximum energy treated the dose would decrease from a maximum of 2.36 mrem/year to a minimum of 0.113 mrem/year with storage times of 7 days and two years respectively. The calculated values represented approximately 0.1 to 2% of the average mrem radiation exposure of humans, 130 mrem/year due to natural environmental radiation.[12]

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